On the Need for Multidimensional Stirling Analysis

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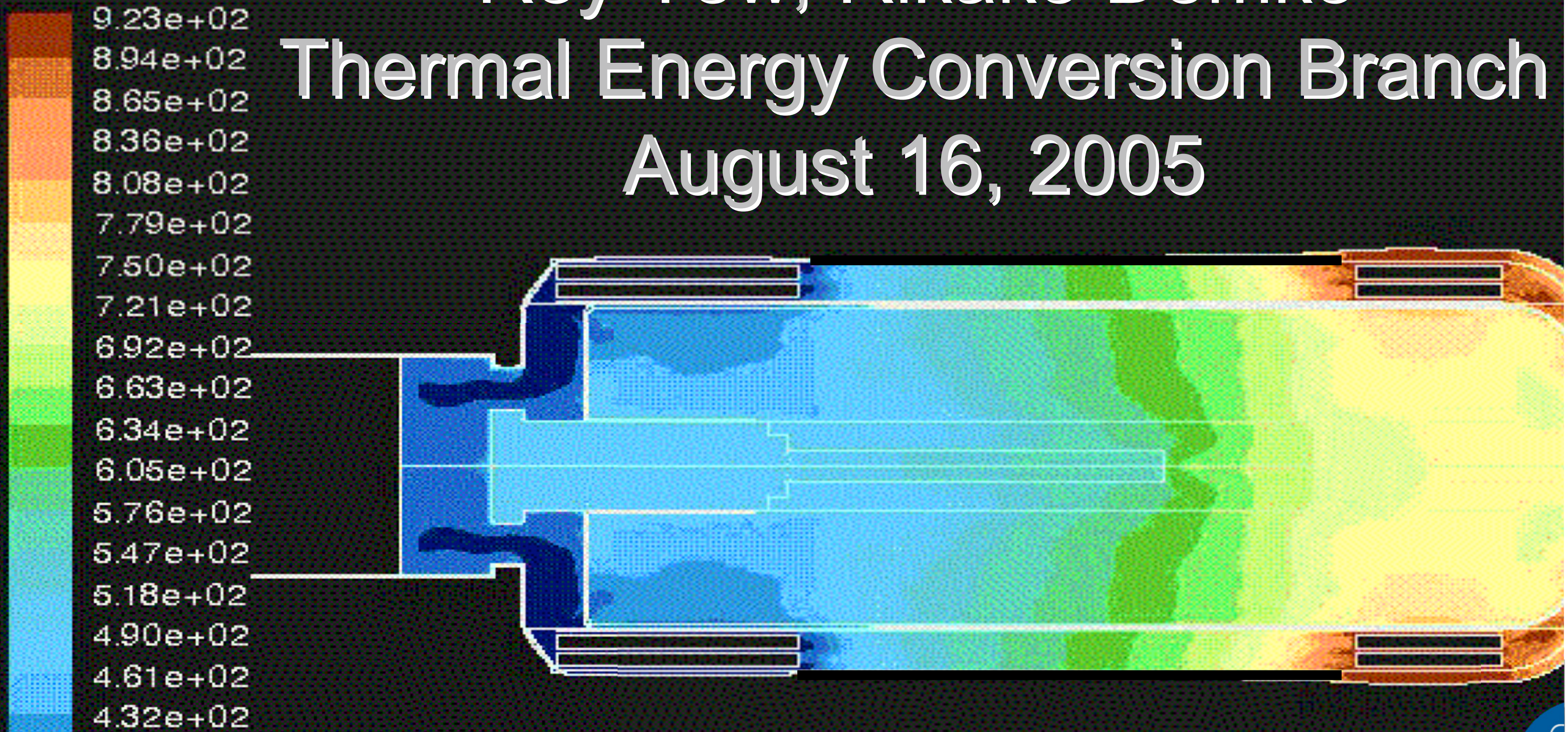
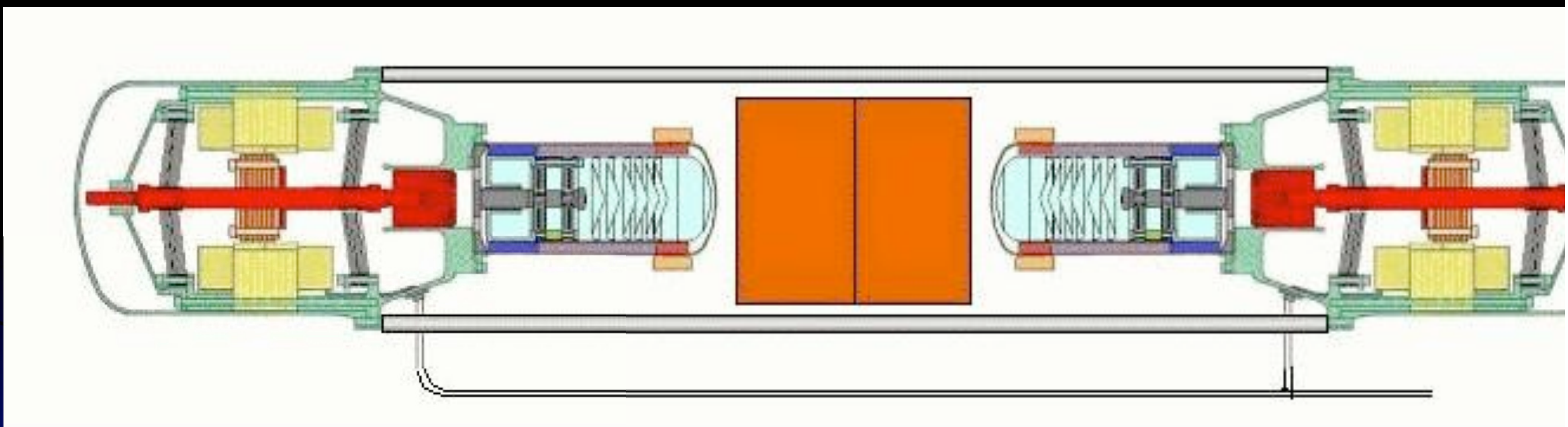


Dual Opposed Convertors

- High Efficiency, Low Mass Space Power



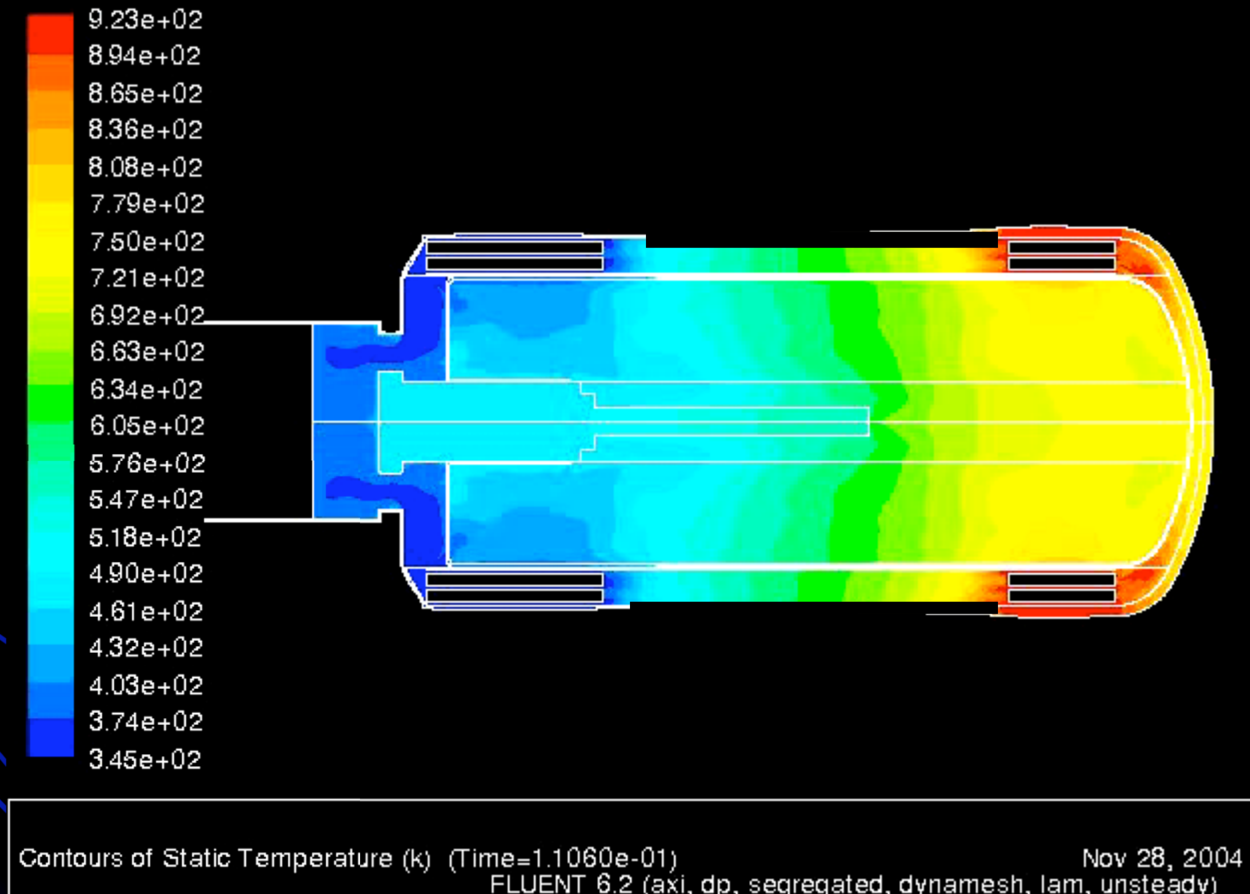
One-Dimensional Analysis

- Sage, LASER, DeltaE, ARCOPTR, REGEN 3.1, others…
- Successful 1D Navier-Stokes solvers
- Set up quickly
- Computations are fast
- Design optimizations are easily done

Need for Multidimensional Modeli

- Simulate all geometrical details and check the one-dimensional results
- Properly simulate flow turbulence and transition
- Provide empirical heat transfer and friction factors
- Integrate all parts to test structures and clearance
- Assist experimentalists with hard to reach data
- Provide fluid-structure interaction capability
- Generate linear reduced order models for controller
- Model large, high-power and low delta T devices
- Generating Linear Models for Controls (Chicatelli)
- Identify areas of excessive flow losses

Axisymmetric Simulation



Flow Characteristics

- Oscillating flow & pressure – affects effective flow and heat transfer properties
- Low mach number (no shocks)
- Compressible due to varying volumes and he transfer
- Laminar, Transitional, and Turbulent
- Conjugate heat transfer

Third Order Analysis

- Finkelstein, Urieli, and Berchowitz
- GLIMPS, Sage – implicit space-time (Gedeor
- HFAST – linearized harmonic analysis
- Martini Engineering, Renfroe – explicit RK
- LASER, DeltaE, ARCOPTR, REGEN3.1
- SDM – electric circuit analogy (Regan, et. al.)

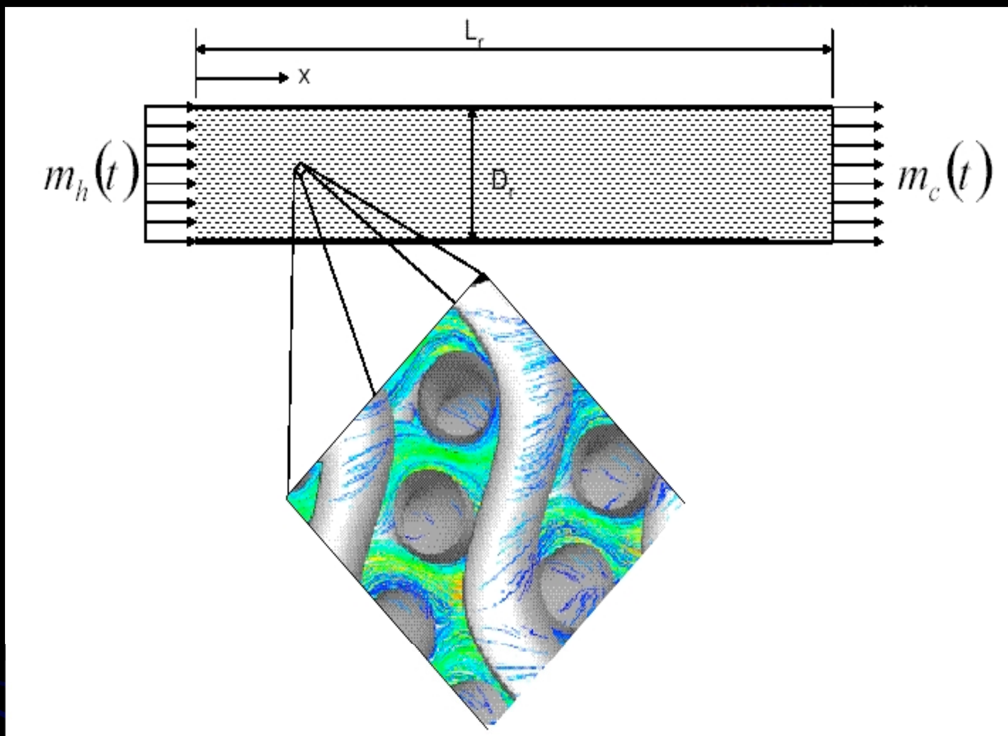
Fourth Order (Multi-Dimensional) Tools

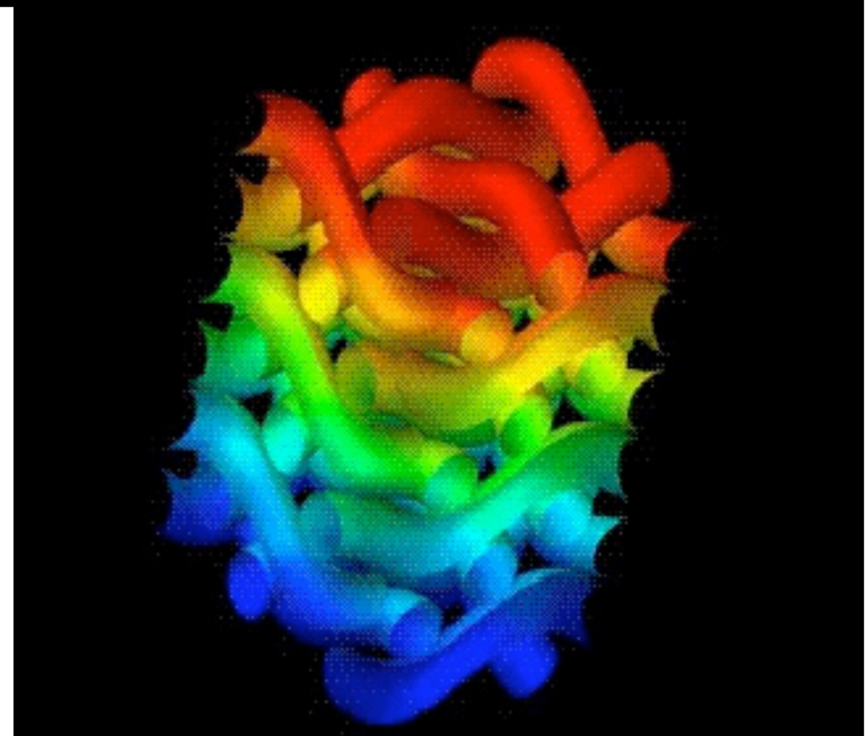
- Modified CAST – Schuerer, later CSU
- CFD-ACE – Used by CSU, later NASA
- Fluent – Used by Infinia, UK, NASA, later CSU
- Star-CD – Used in Korea (Noh, KSME)
- CFX- Preliminary test cases (Demko)
- All utilize low order techniques

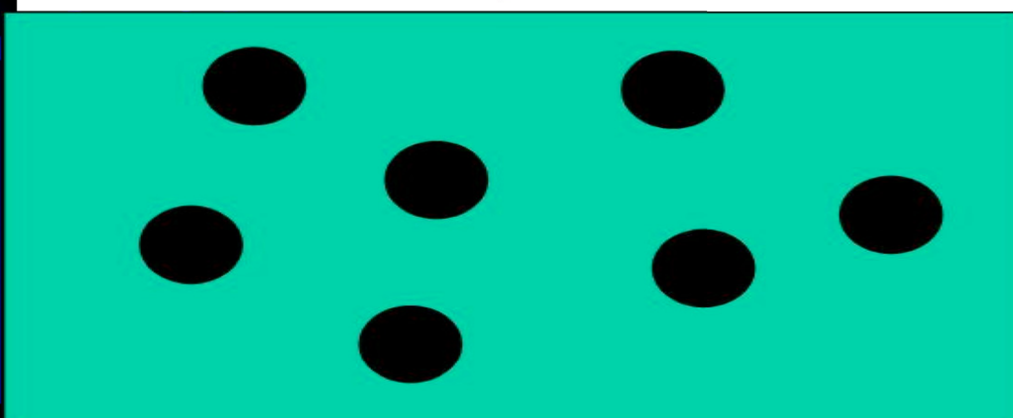
Recent Whole Engine Modeling

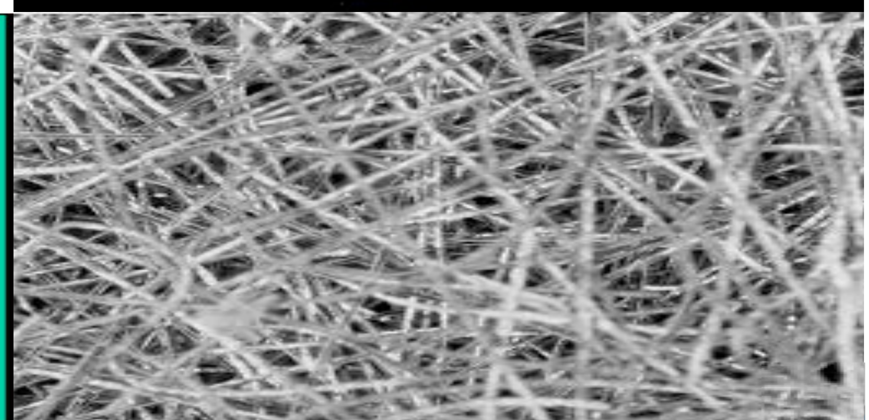
- Mahkamov claims success with 3D gamma (embargoed)
  - Compared to experiment
- Zhang claims success with simplified 3D Free Piston (no conjugate heat transfer)
- Dyson, Tew, Wilson, Demko, 1 hour per axisymmetric (2-D) cycle (Most complete to date but no flexures, shields…)
- Run-time becoming less of an issue

Regenerator Geometry Not 1-D



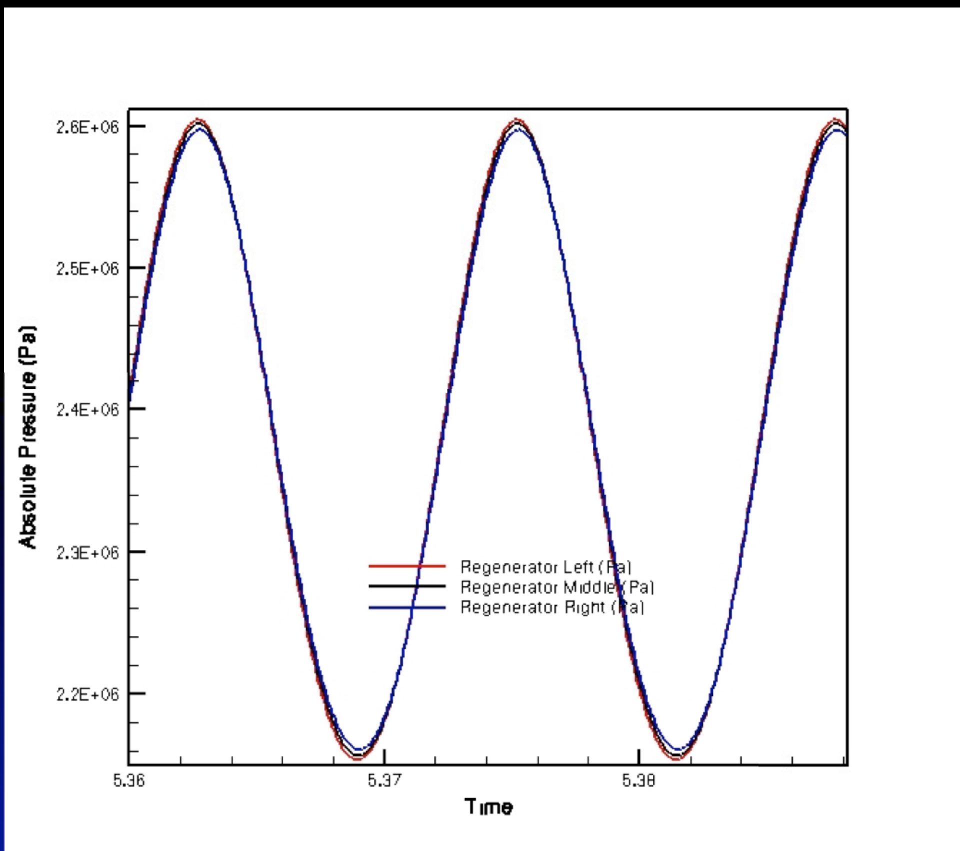


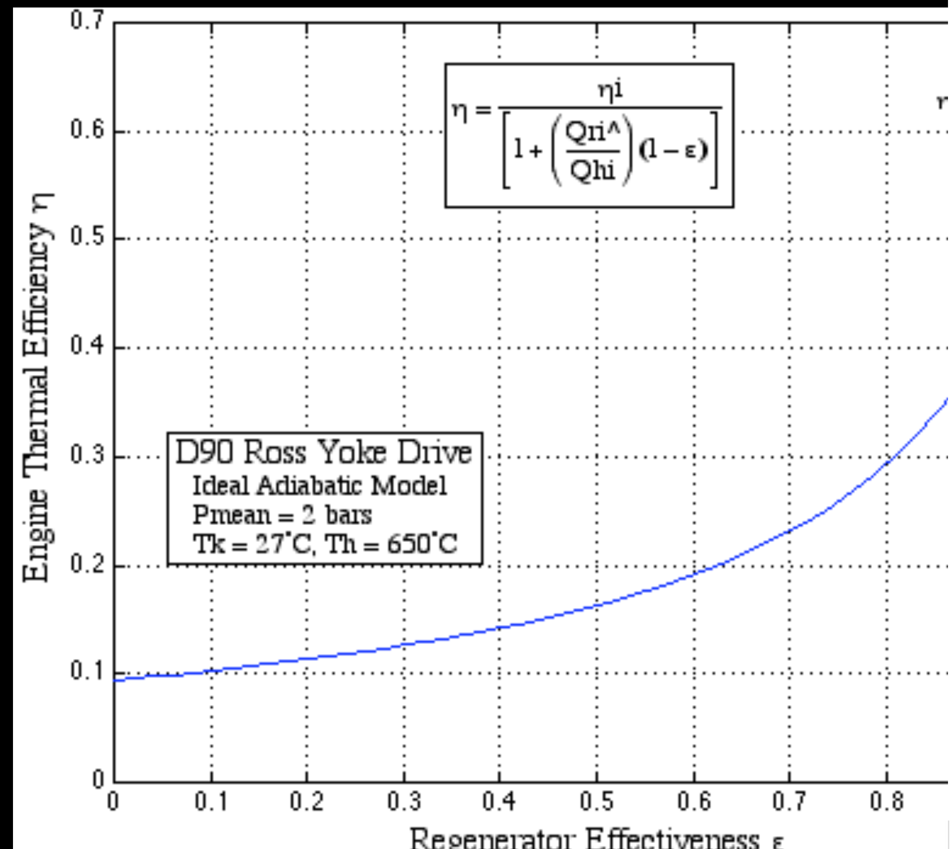




Regenerator Impacts System

- 3 to 40 times more effective heat transfer





Areas Ripe for Multidimensional Analysis

- Seal & Appendix Gap Phenomena (shuttle losses, other heat transfer phenomena)
- Effect of geometrical details such as heat exchanger end effects and regenerator jetting or heat transfer
- Effect of vortices in expansion and compression spaces (causing non-uniform flow in heat exchangers?)
- Flexure Temperatures, important for reliability
- Effect of slight asymmetries on performance
- Displacer gas spring dynamics and losses

Turbulence Modeling

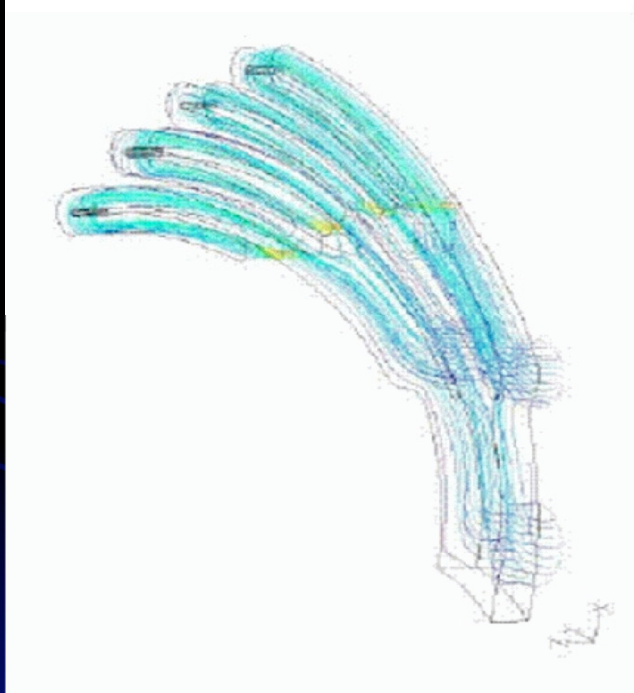
- Turbulence is random not quasi-steady perio
- Turbulence is a fully 3D phenomena
- Transition is a key feature of oscillating flow
- 1D modeling requires empirical data from experiment
- Large Eddy Simulation could be employed

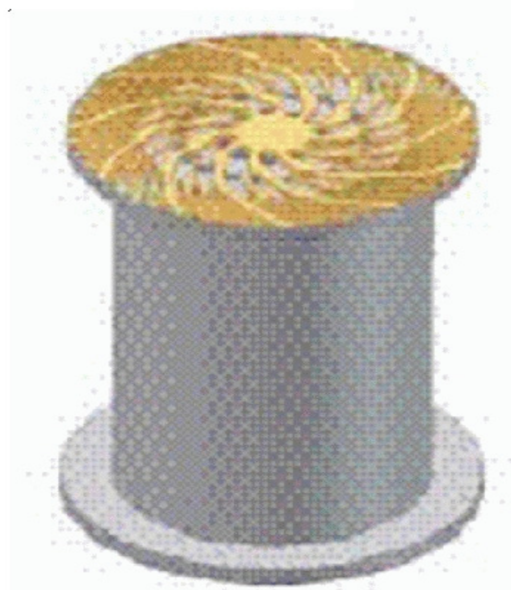
Check One-Dimensional Results

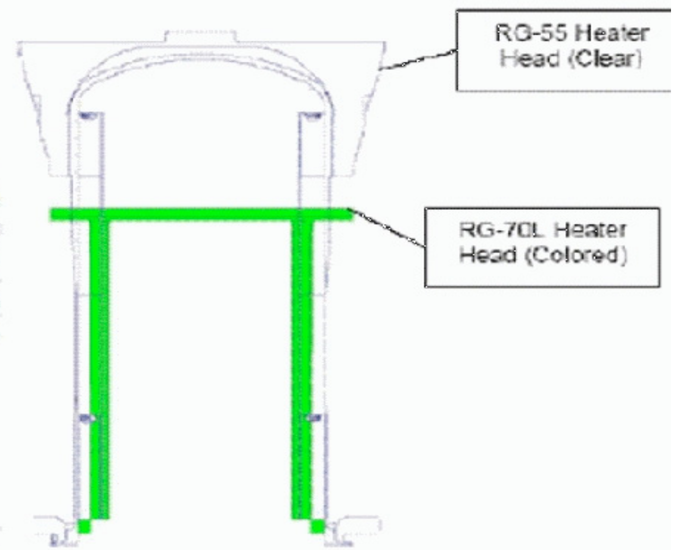
- Inexpensive one-dimensional results depend upon often unknown empirical coefficients
- Check one-dimensional from first principles without resorting to experiment

Flat Head Heater Not 1-D

- Significant error until empirical coefficients adjusted experimentally







S. Qui, STC, IECEC 200

Empirical Coefficients Needed

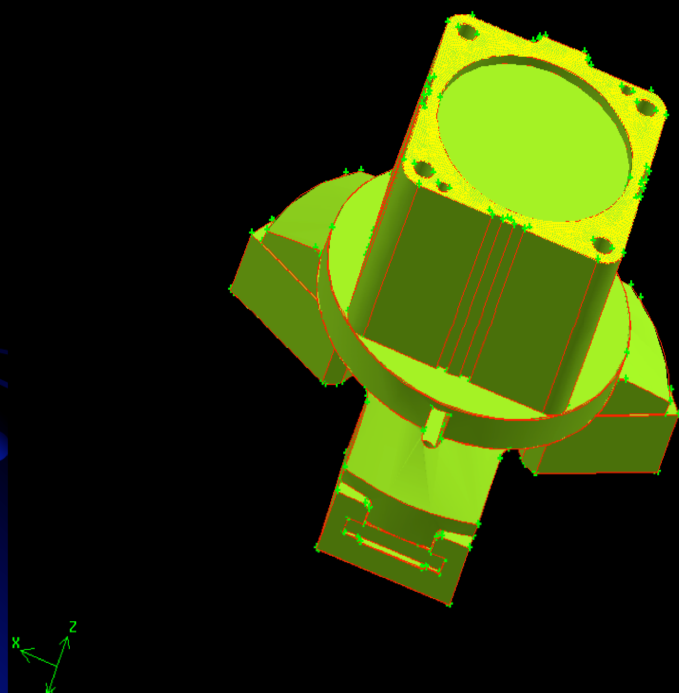
- Empirical coefficients are used to adjust magnitude of frictional pressure drops and to enhance or degrade heat transfer.
- Models can be calibrated after the fact, once test data is availab but may be too late to change hardware designs.
- Utilize CFD to get proper pressure drop and heat transfer coefficients (1-D uses correlations based on regenerator frictior factor tests)
- Sage expected accuracy is 10-20% and improves to 5% once calibrated with test data

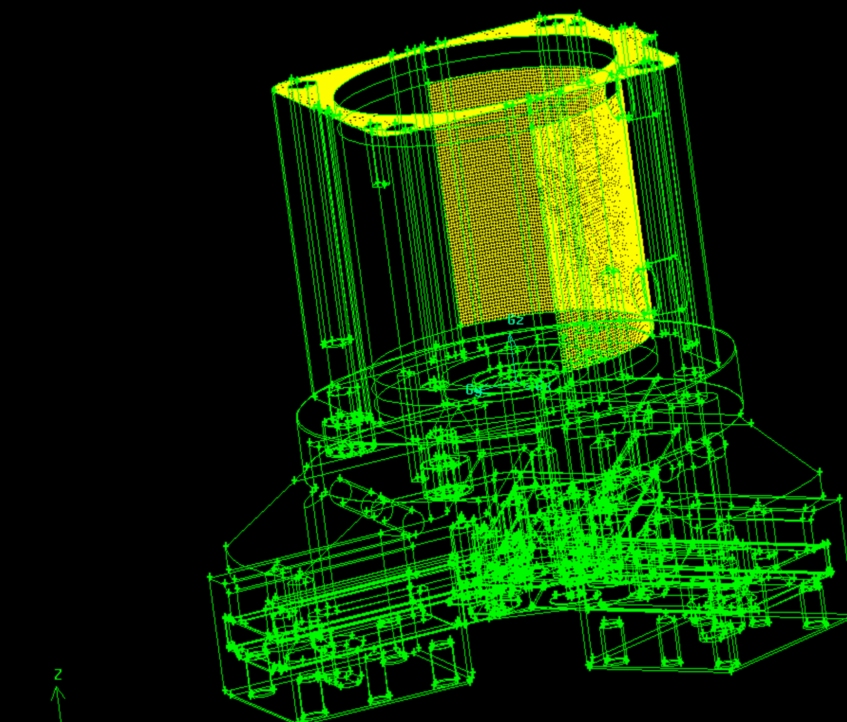
S. Qiu, Stirling Convertor Performance Mapping Test Results for Future Radioisotope Power Systems, STAIF, 2004

S. Qiu, Preliminary Computational Fluid Dynamics Modeling of STC Stirling Eng IECEC 2004

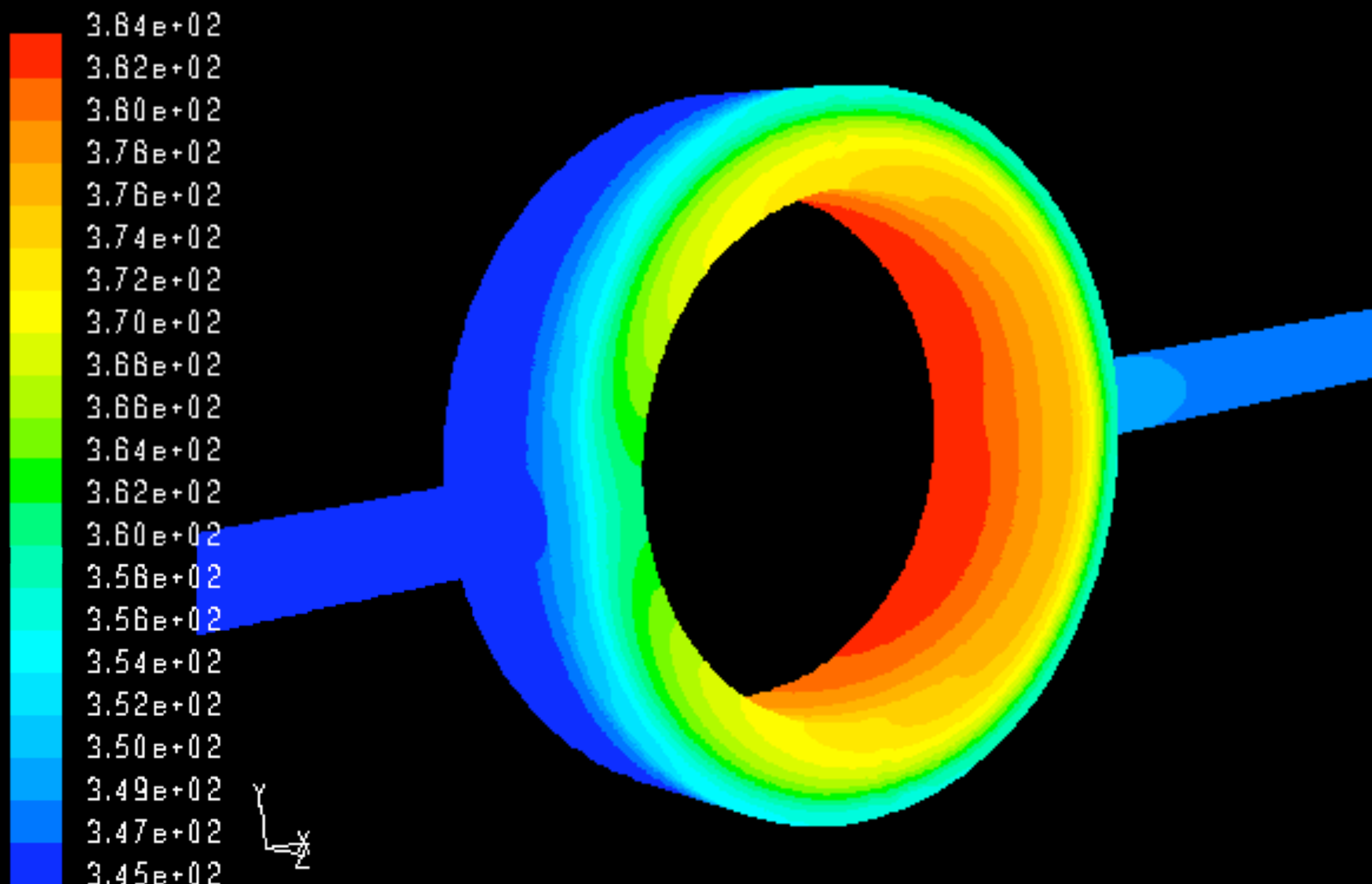
Part Integration

Examine how actual parts fit and interact



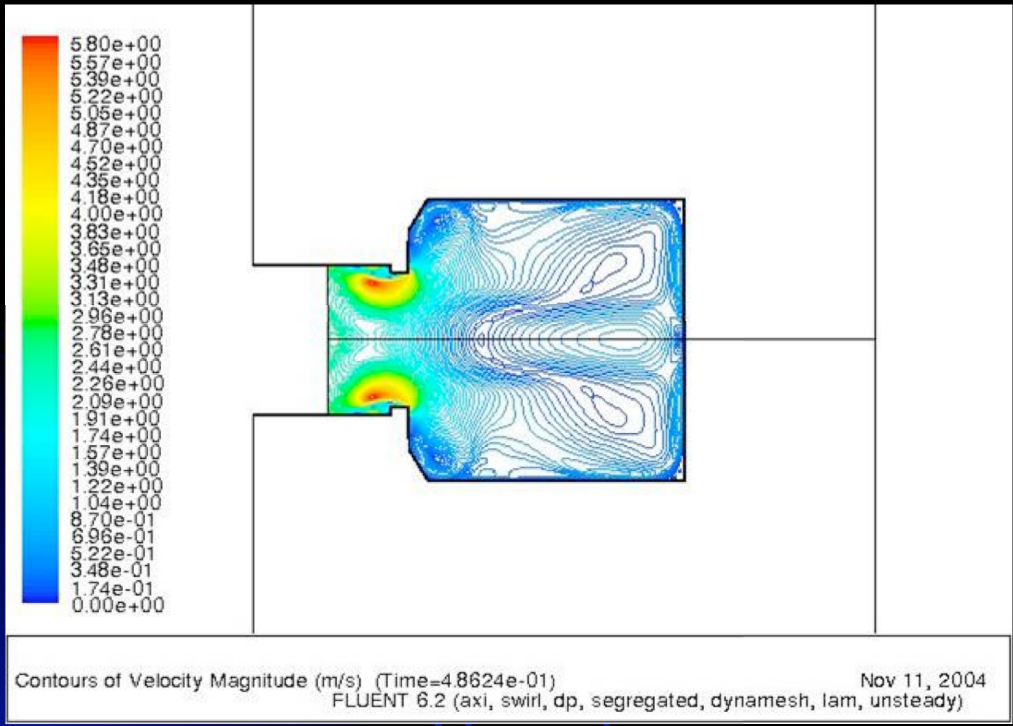


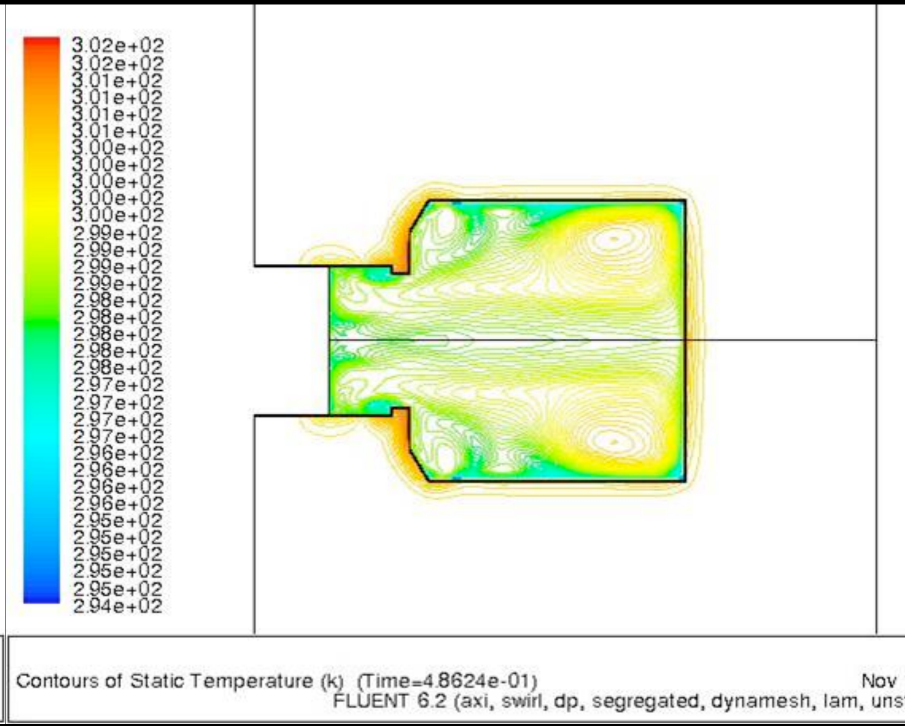
Experiment Design



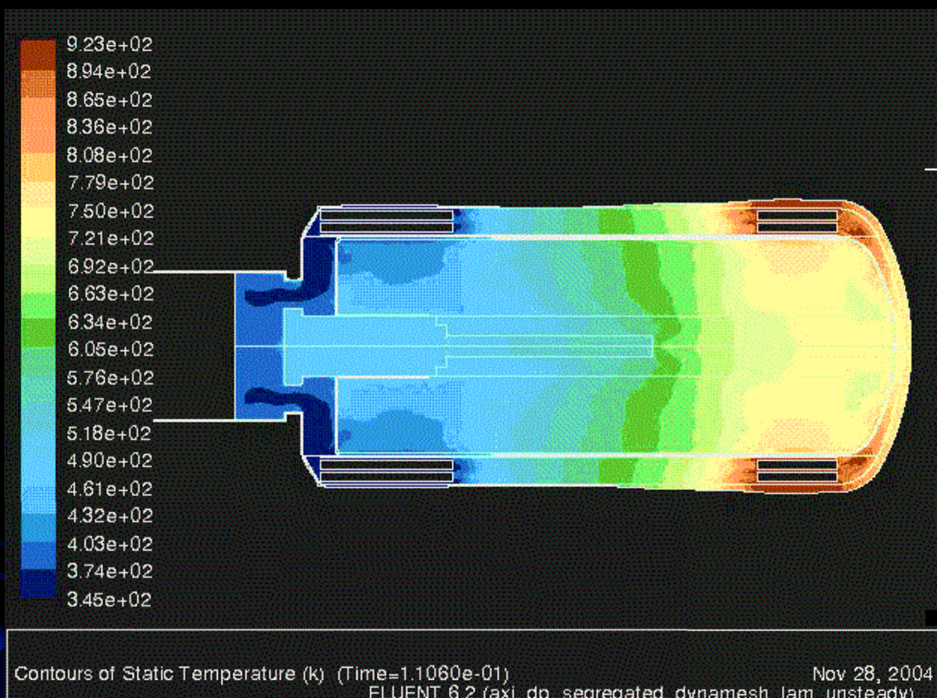
Flow Distribution

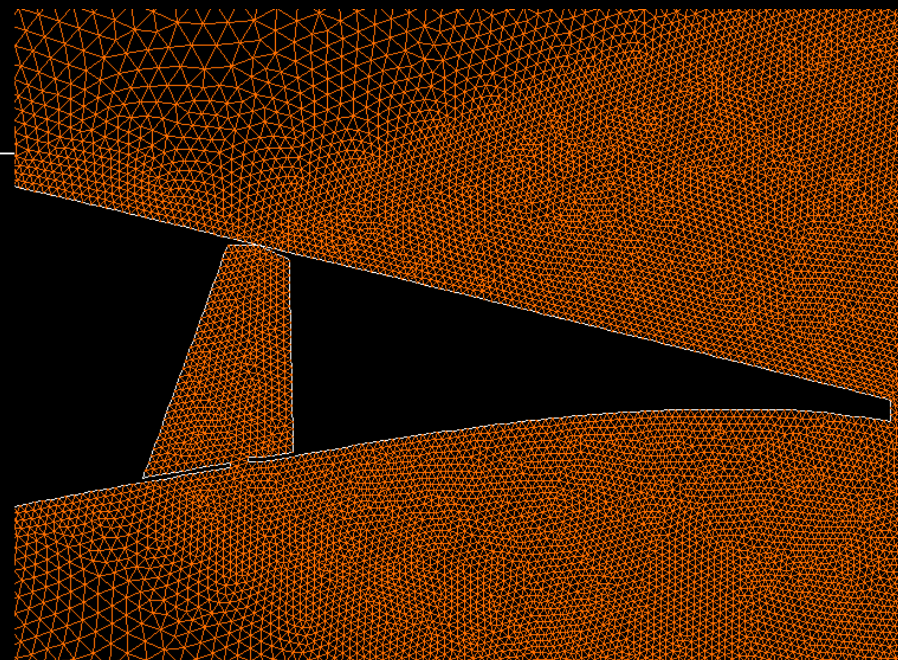
- Sensor Placement, Calibration, Validation





Fluid-Structure Interaction





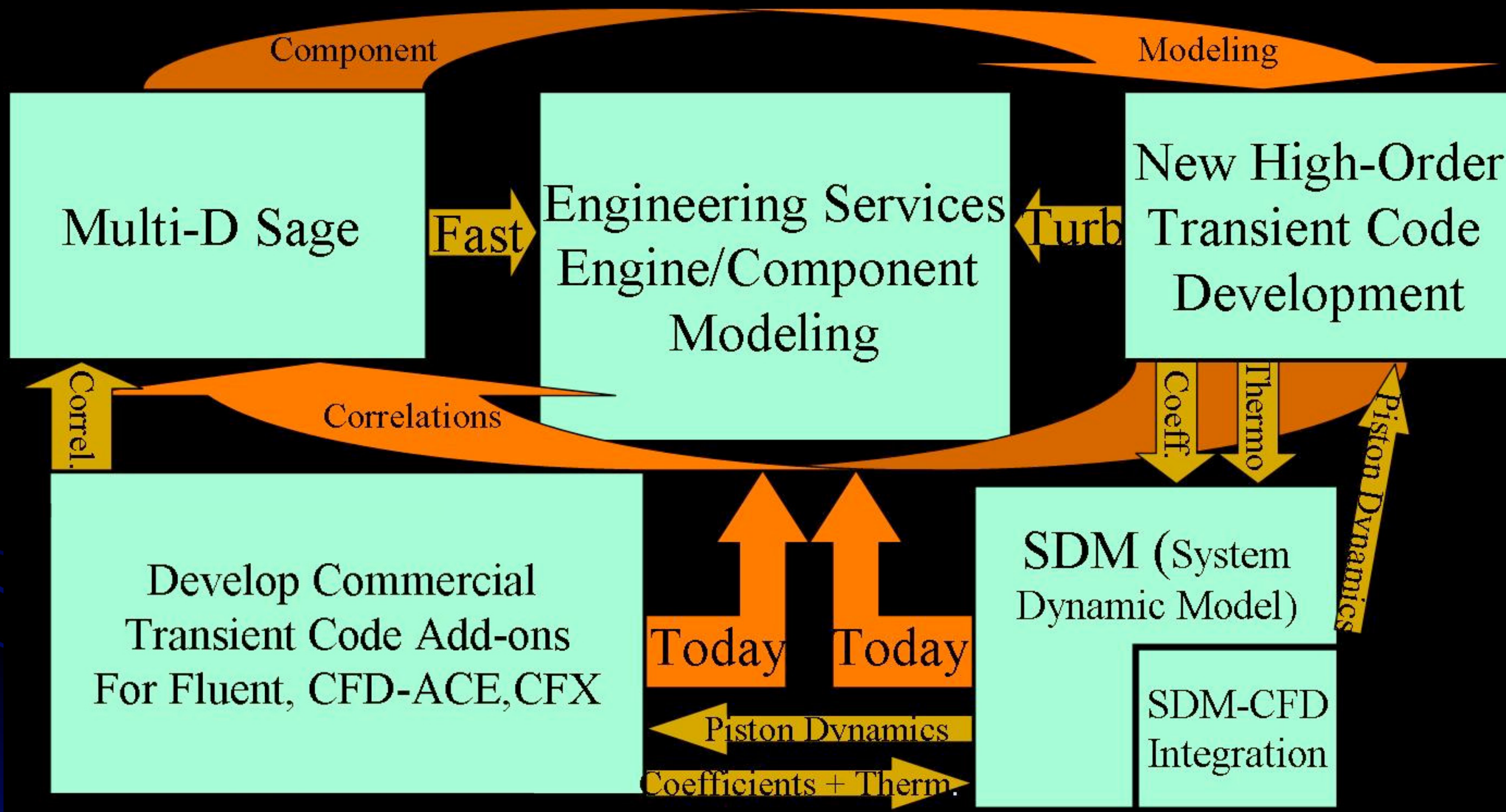
- Radiation Shield, Flexure Bending/Heating

Dimensionality of Losses

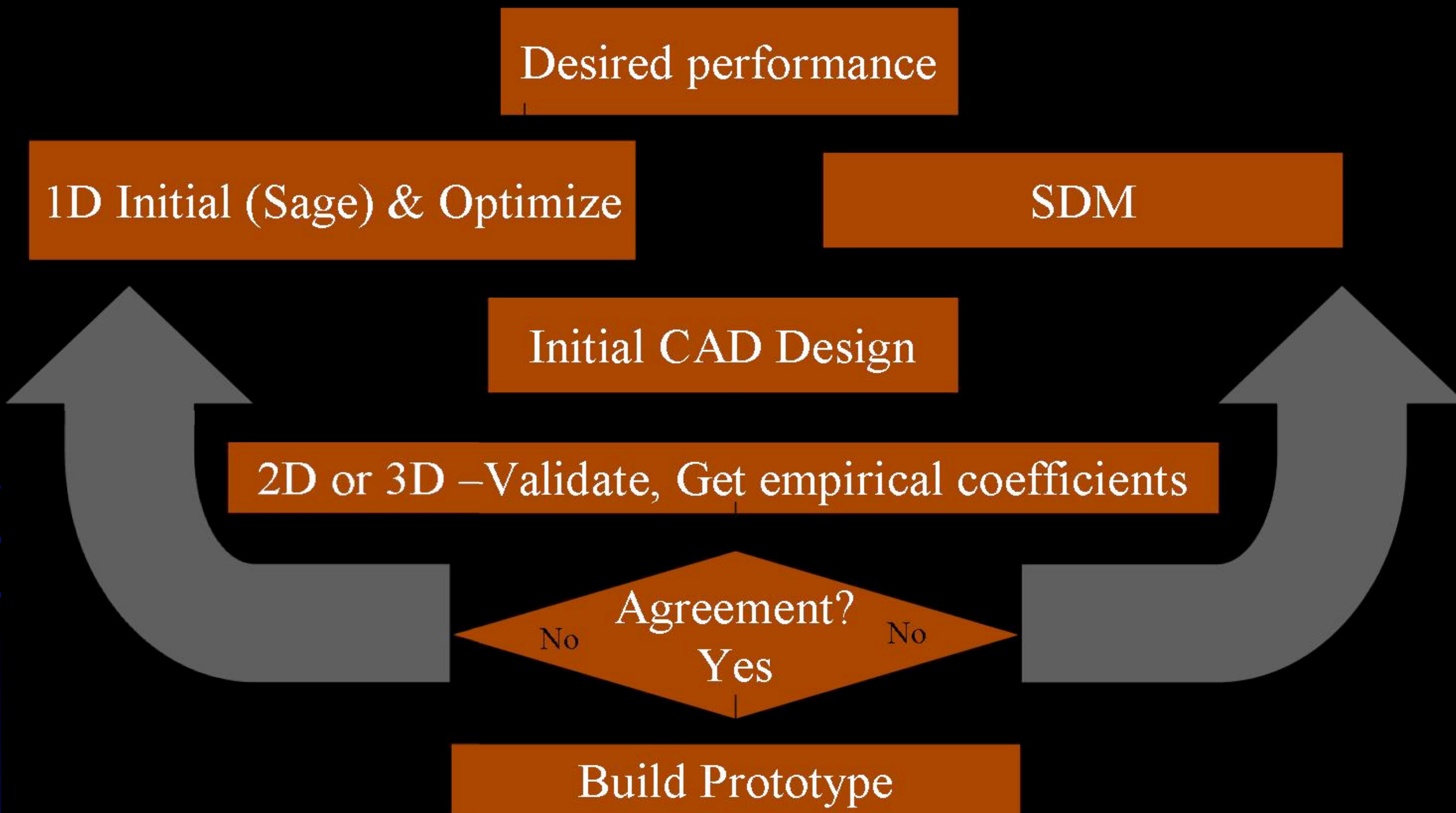
Thermal Conduction+Diffusion+Viscosity=Entropy

TYPE OF LOSS	D	Model
(Enhanced) Thermal conduction in gases and solids	3D	Fourier,Kurzweg,Gedeon Correl.
Gas Thermal and Magnetic Hysteresis	3D	Lumped
Gas Shuttle Losses	2D	?
Gas Bearing, Seal, and Center port Leakage	1-3D	
Electrical resistance losses in windings	1D	I^2R
Pressure drop in heat exchangers (friction and area)	3D	Steady Flow Correlations
Enthalpy transport through regenerators	2D	
Temperature gradients across heat exhangers wall	1D	Use Q => Delta
Friction in seals and crank mechanisms	1D	Use forces

Design and Integration Analysis Options



Comprehensive Analysis Tree



Conclusions

- Need 1D, 2D, and 3D Stirling design tools.
- The combination of all three paradigms provi
  for initial design, empirical coefficient adjustment, optimization, and final prototype demonstration before the first part is cut.